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Flow and heat exchange calculation of waxy oil in the industrial pipeline

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ABSTRACT

Waxy oil transportation in the industrial pipeline becomes impossible at temperatures below pour point. Pour point depressant application allows transportation by decreasing pour point and increasing waxy oil fluidity. The novelty of the research lies in modeling waxy oil transportation with pour point depressant in the industrial pipeline. "Randep-5102" pour point depressant with a dose of 200 ppm is used for pumping of waxy oil. Continuity, momentum and energy equations with closing relations were solved by the numerical method. The verification of the theoretical analysis was carried out with experimental data measured by the SCADA (supervisory control and data acquisition) system sensors along the industrial pipeline length. The results of comparing thermo-hydraulic calculations with experimental data confirmed the effectiveness of pour point depressant for pumping of waxy oil at temperatures below pour point.

1. Introduction

Waxy oils from Kazakhstani fields have high-viscosity due to the content of asphaltenes and resins, as well as high-pour-point [1,2]. Difficulties in pumping of waxy oil are caused by the significant dependence of viscosity and yield stress on temperature. Oil temperature reduction below pour point can cause oil solidification in the pipeline, leading to the complete stop of pumping and significant costs for its resumption [3,4].

Waxy oil transportation is carried out by the hot pumping method [5–7] or using pour point depressant [8–18]. Hot pumping with trace heating is very expensive. Pour point depressant allows [8–18]: 1) reducing pour point; 2) decreasing dynamic viscosity and increasing oil fluidity.

The effectiveness of pour point depressant for pumping of waxy oil has been shown in the Western European oil pipelines such as Rotterdam-Rhine, Ile-de-France, Finnart-Grangemouth. The addition of pour point depressant in the amount of 0.12–0.15% by weight led to a decrease in dynamic viscosity by two to four times and yield stress by fifty to seventy times [19].

On the Hui-Ning oil pipeline, which is located in China, pour point depressant with a concentration of 50 ppm was used, because of which pour point was reduced from 24 to 8 °C. The similar results were obtained on the subsea oil pipelines of the Mumbai and High-Uran fields in India and on the oil pipelines in Sudan and New Zealand [19].

Review articles [8–12] are mainly devoted to the description of various types of pour point depressant, the pumping method, increasing fluidity and lowering pour point of waxy oil. It is noted that a small dose of pour point depressant changes viscosity, yield

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stress and pour point of oil. Other characteristics such as density, heat capacity, thermal conductivity do not change. The increase in fluidity is explained by the decrease in viscosity, and the hydraulic resistance coefficient obeys the well-known law of resistance in the pipeline [20–24].

Experimental studies of oil transportation with pour point depressants in the industrial pipeline were carried out in Refs. [25–27]. Experimental results show that waxy oil treated with pour point depressant acquires an obvious modifying effect.

Simulating waxy oil with pour point depressant is carried out mainly to restart the pipeline after shutdown [28–32]. Pour point depressant allows reducing the restart pressure and ensures the safe operation of the pipeline.

The simulation results of waxy oil pumping with pour point depressant in the industrial pipeline are practically absent.

“Randep-5102″ pour point depressant application with a concentration of 200 ppm on the “

Dzhumagaliev–Chulak-Kurgan” industrial pipeline, which is located in Kazakhstan, reduces pour point from 12 to 0 °C [2].

This paper presents the results of mathematical simulation of pumping with pour point depressant in the industrial pipeline.

2. The mathematical model

The “Dzhumagaliev–Chulak-Kurgan” industrial pipeline profile and the station location diagram are shown in Fig. 1. The profile has elevation points above sea level, which creates static oil pressure in the pipeline.

Non-isothermal flow of waxy oil flows from north (the “Dzhumagaliev” station) to south (the “Chulak-Kurgan” station). In the paper, u_0 denotes the flow velocity, t_w gives the soil temperature and t_0 is the inlet oil temperature. Soil temperature less than inlet oil temperature.

Pumping is carried out by the pumps of the “Dzhumagaliev” head station.

A pipeline section length of L = 331 km is much larger than a pipeline diameter of $D_1 = 0.8$ m, therefore, pumping is calculated using the one-dimensional model.

Continuity, momentum and energy equations of flow can be written in the general form [5]:

$$\frac{\partial \rho}{\partial \tau} + \frac{\partial \rho u}{\partial x} = 0 \tag{1}$$

$$\rho \frac{\partial u}{\partial \tau} + \frac{\partial p}{\partial x} = -\zeta(\mathrm{Re}, \varepsilon)\frac{\rho u|u|}{2D_1} - \rho g \sin \beta(x) \tag{2}$$

$$\frac{\partial t}{\partial \tau} + u\frac{\partial t}{\partial x} = -\frac{4k}{\rho c_p D_1}(t - t_w) + \frac{ugh}{c_p} \tag{3}$$

In equations (1)–(3), τ is the time, x is the coordinate, p is the pressure, ρ is the density, c_p is the heat capacity, u is the velocity, t is the temperature, $\zeta(\mathrm{Re}, \varepsilon)$ is the hydraulic resistance coefficient, $\mathrm{Re} = \rho u D_1/\mu_p$ is the Reynolds number, k is the heat transfer coefficient, ugh/c_p is the dissipation of kinetic energy into heat, $h = \frac{1}{\rho g}\left(-\frac{\partial p}{\partial x}\right)$ is the head loss per unit length of the pipeline (hydraulic gradient), ε is the degree of roughness, D_1 is the pipeline diameter, t_w is the soil temperature, $\beta(x)$ is the pipeline inclination angle, g is the gravitational acceleration.

The experimental data of oil density dependence on temperature are described by the empirical formula [2,5]:

$$\rho(t) = \rho_{20}[1 + \zeta \cdot (20 - t)](kg/m^3) \tag{4}$$

where $\zeta = 0.000738\left(\frac{1}{^\circ C}\right)$ is the oil volume expansion coefficient.

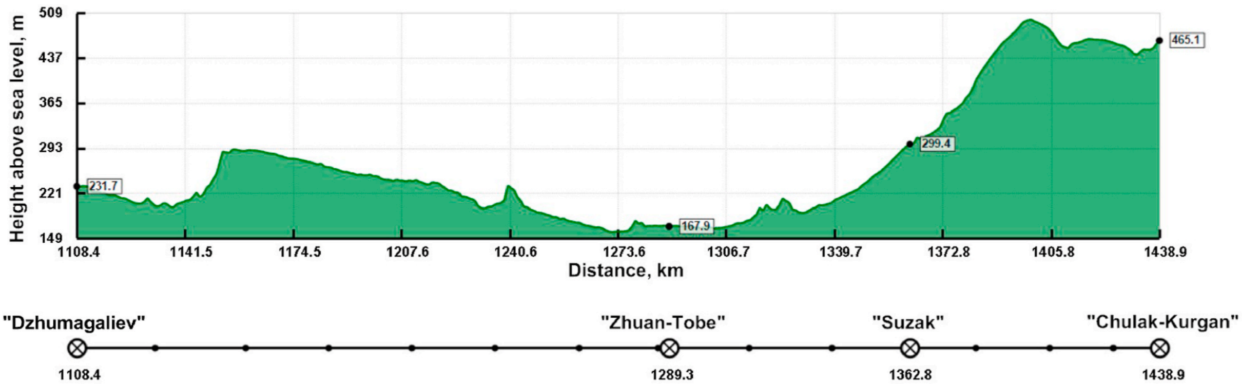

Fig. 1. Industrial pipeline profile and station location diagram.

In the range of oil temperature variation in the industrial pipeline from 10 to 40 °C, density remains practically constant $\rho = \rho_0$. Oil flow can be considered an incompressible fluid. The oil volumetric flow rate is maintained and the flow rate remains constant along the pipeline length.

In this case, the mathematical model (1)–(3) is simplified and takes the form:

$$\frac{\partial p}{\partial x} = -\zeta(\mathrm{Re},\varepsilon)\frac{\rho_0 u^2}{2D_1} - \rho_0 g \sin\beta(x) \tag{5}$$

$$\frac{\partial t}{\partial \tau} + u\frac{\partial t}{\partial x} = -\frac{4k}{\rho_0 c_p D_1}(t - t_w) + \frac{ugh}{c_p} \tag{6}$$

The system of equations (5), (6) is solved with initial and boundary conditions:

$$t(0,x) = t_w(x), 0 \le x \le L \tag{7}$$

$$t(\tau,0) = t_0, p(\tau,0) = p_0, 0 \le \tau \le T \tag{8}$$

3. Closing relations

The Reynolds number Re in $\zeta(\mathrm{Re},\varepsilon)$ is determined by oil viscosity $\mu_p(t)$. As experiments show, viscosity $\mu_p(t)$ and yield stress $\tau_0(t)$ of high-pour-point oil are strongly dependent on temperature. In the industrial pipeline, due to heat exchange with the environment, oil temperature decreases, while viscosity $\mu_p(t)$ and yield stress $\tau_0(t)$, on the contrary, increases.

Fig. 2 shows waxy oil dynamic viscosity $\mu_p(t)$ and yield stress $\tau_0(t)$ graphs, treated with and without "Randep-5102″ pour point depressant. Dependences $\mu_p(t)$ and $\tau_0(t)$ on temperature were obtained using the regression model by processing experimental data in the form:Without pour point depressant:

$$\mu_p(t) = 0.3154\cdot\exp(-0.234\cdot t),\quad \tau_0(t) = 15948\cdot\exp(-0.998\cdot t) \tag{9}$$

with pour point depressant:

$$\mu_p(t) = 0.0459\cdot\exp(-0.115\cdot t),\quad \tau_0(t) = 0.408\cdot\exp(-1.443\cdot t) \tag{10}$$

Dependences of $\mu_p(t)$ and $\tau_0(t)$ with and without consideration of pour point depressant sharply increase from temperature 0 °C and 12 °C, respectively (see Fig. 2). A sharp increase of dynamic viscosity $\mu_p(t)$ and yield stress $\tau_0(t)$ is expressed by the presence of pour point.

Oil temperature reduction leads to wax crystallization and heat release of phase transition. Accounting for the total amount of latent heat can be determined by the apparent heat capacity method. In this case, a change in heat capacity can be represented in the form [33]:

$$c_p = \begin{cases} c_s & t < t_s \\ c_{in} & t_s \le t \le t_l \\ c_l & t > t_l \end{cases} \tag{11}$$

where

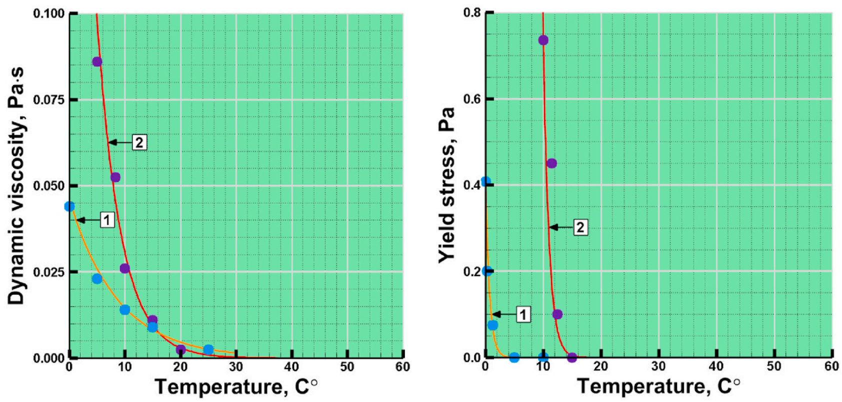

Fig. 2. Dependences of dynamic viscosity $\mu_p(t)$ and yield stress $\tau_0(t)$ on temperature: 1 - with pour point depressant, 2 - without pour point depressant.

$$c_{in} = \left\{ \int_{t_s}^{t_l} c_l(t)dt + \psi I_{1\to 2} \right\} / (t_l - t_s) \tag{12}$$

Above, c_s is in the solid phase, c_{in} is in the transition phase, c_l is in the liquid phase, $t_l$and t_s are the initial and final value of wax appearance temperature in oil flow, ψ is the paraffin content in oil composition, $I_{1\to 2}$ is the specific enthalpy of paraffin phase transition.

The experimental data of waxy oil heat capacity dependence are described by the Krego's empirical formula [5]:

$$c_l(t) = (53357 + 107.2 \cdot t) / \sqrt{\rho_0}, J / kg \cdot {}^\circ C$$

where ρ_0 is the oil density at a temperature of 20 °C.

In the calculations, the following values were taken: $t_l = 32^\circ$C, $t_s = 15^\circ$C, $I_{1\to 2} = 9.8$ kcal/kg, $\psi = 0.15$.

Substituting $c_l(t)$ into integral (12), it is possible to determine oil heat capacity dependence on temperature during wax crystallization.

The hydraulic resistance coefficient $\zeta(\mathrm{Re}, \varepsilon)$ is found by the Altshul formula [23]:

$$\zeta(\mathrm{Re}, \varepsilon) = 0.11 \cdot \left(\frac{68}{\mathrm{Re}} + \varepsilon \right)^{0.25} \tag{13}$$

The heat transfer coefficient value k is found according to the standard formula [5]:

$$\frac{1}{kD_1} = \frac{1}{\alpha_1 D_1} + \sum_{i=1} \frac{1}{2\lambda_i} \ln \frac{D_{i+1}}{D_i} + \frac{1}{\alpha_2 D_2} \tag{14}$$

Here k is the heat transfer coefficient from oil to the environment; α_1 and α_2 are the internal and external heat transfer coefficients, accordingly; D_2 is the pipeline outer diameter; D_i are the outer diameters of insulation layers; λ_i are the thermal conductivity coefficients of metal and insulation coating layers.

As shown in calculations, heat transfer coefficient k mainly depends on the external heat transfer coefficient, determined by the Forchheimer-Vlasov formula [5]:

$$\alpha_2 = \frac{2\lambda_w}{D_2 \ln \left[\frac{2H}{D_2} + \sqrt{\left(\frac{2H}{D_2} \right)^2 - 1} \right]} \tag{15}$$

where λ_w is the soil thermal conductivity coefficient, H is the pipeline laying depth. Soil temperature t_w and the soil thermal conductivity coefficient λ_w were obtained from the SCADA system sensor data.

4. The numerical calculation method

The numerical calculations of the system of equations (5), (6) with initial and boundary conditions (7), (8) and closing relations (9)–(15) were carried out by the finite difference method [34,35]. Let's divide the segment $[0, L]$ into N parts with a step h_1, and the time interval $[0, T]$ into M parts with a step $\Delta\tau$ and build the difference mesh:

$$Q_{\Delta\tau h_1} = \{ \tau_i, x_j | \tau_i = i\Delta\tau, \Delta\tau = T / M, i = 1, M; x_j = jh_1, h_1 = L / N, j = 1, N \}$$

Temperature values are denoted by $t_i^j = t(\tau_i, x_j)$ at the node (τ_i, x_j) of the mesh $Q_{\Delta\tau h_1}$.

equations (6)–(8) are approximated by the implicit difference scheme:

$$\frac{t_j^{i+1} - t_j^i}{\Delta\tau} + u \frac{t_j^{i+1} - t_{j-1}^{i+1}}{h_1} = -\frac{4k}{\rho_0 c_{pj}^i} \left(t_j^i - t_w \right) + \frac{ugh_j^i}{c_{pj}^i}, \quad i = 1, M-1; \ j = 1, N, \tag{16}$$

$$t_j^0 = t_w(x_j), j = 1, N; t_1^i = t_0(\tau_i), \quad i = 1, M \tag{17}$$

equations (5) and (8) are approximated by the difference scheme:

$$\frac{p_j^{i+1} - p_{j-1}^{i+1}}{h_1} = -\zeta\left(\mathrm{Re}_j^i, \varepsilon \right) \frac{\rho_0 u^2}{2D_1} - \rho_0 g \sin(x_j), \quad i = 1, M-1; j = 1, N \tag{18}$$

$$p_1^i = p_0(\tau_i), \quad i = 1, M \tag{19}$$

Using marching order method, temperature values t_j^{i+1} are found from (16), (17), and pressure values p_j^{i+1} are found from (18), (19) at the nodes of the difference mesh. The values of the Reynolds number Re_j^{i+1}, heat capacity $c_{pj}^{i+1}(t_j^{i+1})$, viscosity $\mu_{pj}^{i+1}(t_j^{i+1})$ are found on the computed temperature value t_j^{i+1}, and on the distribution of pressure p_j^{i+1} is calculated h_j^{i+1}. The iterative process of calculation t_j^{i+1},

p_j^{i+1} continues until the convergence conditions are met with an accuracy of 0.001.

5. Calculation method validation

The calculation method was verified by comparing with the experimental SCADA system data. The SCADA system sensors measure pressure, temperature, oil flow rate and soil temperature in real-time mode. The industrial pipeline section is considered in Fig. 3 and Fig. 4.

Experimental temperature data make it possible to find the values of dynamic viscosity $\mu_p(t)$, the Reynolds number $\mathrm{Re} = \rho u D_1 / \mu_p$. The Altshul formula (13) with the known degree of the pipeline roughness $\varepsilon = \delta / D_1, \delta = 0.001m$ determines the hydraulic resistance coefficient $\zeta(\mathrm{Re}, \varepsilon)$.

In the numerical calculations of the system of equations 16–19, it is also possible to determine the hydraulic resistance coefficient $\zeta(\mathrm{Re}, \varepsilon)$. Experimental and calculated values $\zeta(\mathrm{Re}, \varepsilon)$ comparison in the industrial pipeline was shown in Fig. 3.

The agreement between calculated and experimental values $\zeta(\mathrm{Re}, \varepsilon)$ shows the reliability of the calculation method of the proposed mathematical model (see Fig. 3).

The calculation method is implemented in the SmartTran software [36] and is used to carry out thermo-hydraulic calculations for pumping of waxy oil in the "Dzhumagaliev–Chulak-Kurgan" industrial pipeline.

6. Discussion of practical application in the industrial pipeline

The calculations were carried out at given flow rates, waxy oil temperature at the station outlet and soil temperature. Density value is $\rho_{20} = 815$ kg/m^3, the pipeline laying depth is $H = 2.0$ m. Figs. 5–7 show hydraulic head (top graph), pressure (middle graph), waxy oil temperature and soil temperature (bottom graph) at the "Dzhumagaliev–Chulak-Kurgan" industrial pipeline. The pink, green, blue, red and burgundy lines show the calculated data of hydraulic head, pipeline profile, pressure, oil temperature and soil temperature, respectively. The black points illustrate the experimental data of hydraulic head, pressure and oil temperature. The burgundy points show soil temperature. The experimental data were obtained from the SCADA system sensors. The hydraulic head determines the head loss along the length of the pipeline.

Waxy oil flow with a flow rate of 735.3 m^3/h is pumped without pour point depressant (see Fig. 5). In this case, thermo-hydraulic calculations were carried out without pour point depressant using the viscosity dependence on temperature (9). Waxy oil pressure and temperature at the "Dzhumagaliev" station, equal to 27.1 bar and 25.3 °C, decrease to 0.7 bar and 20.6 °C at the "Chulak-Kurgan" station, respectively. Soil temperature varies from 18.4 to 23.2 °C.

Comparing the calculation results of waxy oil hydraulic head, pressure and temperature shows agreement with the experimental data of the SCADA system sensors (see Fig. 5).

During the cold period of pipeline operation, waxy oil is treated with "Randep-5102″ pour point depressant. Waxy oil processing is carried out at the "Kumkol" station, located 200 km from the "Dzhumagaliev" station. Pour point depressant remains in effect until the final point of the "Dzhumagaliev–Chulak-Kurgan" industrial pipeline.

Thermo-hydraulic calculations were carried out using the viscosity dependence on temperature (10).

Fig. 6 shows the calculated data at a waxy oil flow rate of 681 m^3/h and soil temperature in the range from 5.6 to 9.1°C. Waxy oil temperature at the "Dzhumagaliev" station outlet is 18.8 °C and decreases at the "Chulak-Kurgan" station to 10.4 °C due to heat exchange with the environment. Waxy oil flow with pour point depressant retains fluidity, since pour point is equal to 0°C.Whereas waxy oil without pour point depressant could solidify and lead to the complete stop of pumping at the "Dzhumagaliev–Chulak-Kurgan" industrial pipeline.

As can be seen from Fig. 6, the calculation results of hydraulic head, pressure and temperature are consistent with the experimental data of the SCADA system.

The similar results were obtained at a waxy oil flow rate of 745.8 m^3/h and soil temperature in the range from 5.5 to 9.9°C (see Fig. 7).

Thus, "Randep-5102″ pour point depressant application at low soil temperatures makes it possible to transport waxy oil in the "Dzhumagaliev–Chulak-Kurgan" industrial pipeline.

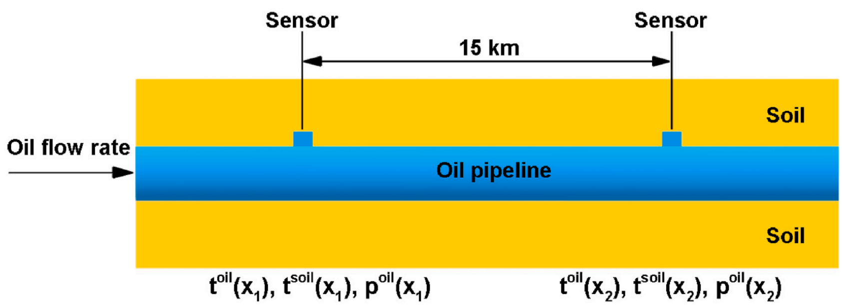

Fig. 3. Pipeline section diagram.

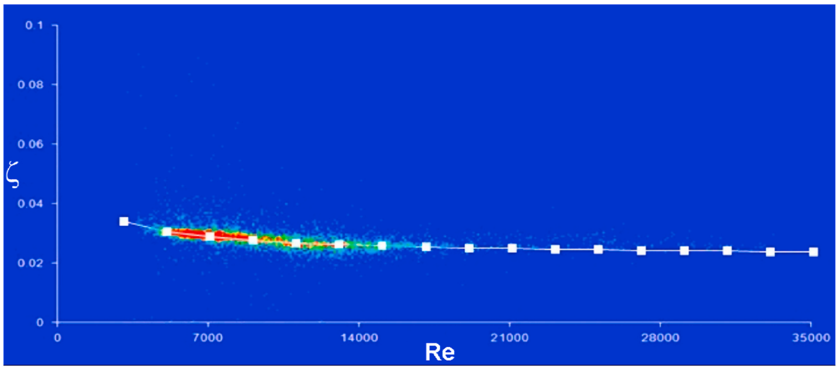

Fig. 4. Calculated and experimental values $\zeta(\mathrm{Re}, \varepsilon)$ comparison.

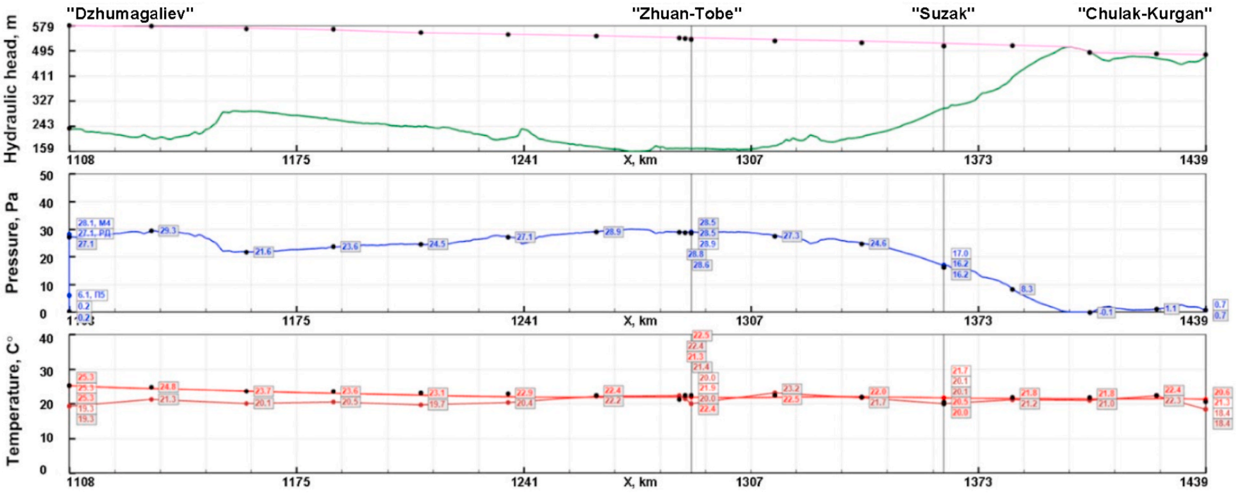

Fig. 5. Experiments (points) and calculations (lines) of hydraulic head, pressure and temperature at the "Dzhumagaliev–Chulak-Kurgan" industrial pipeline at a flow rate of 735.3 m^3/h and an outlet temperature of 25.3 °C.

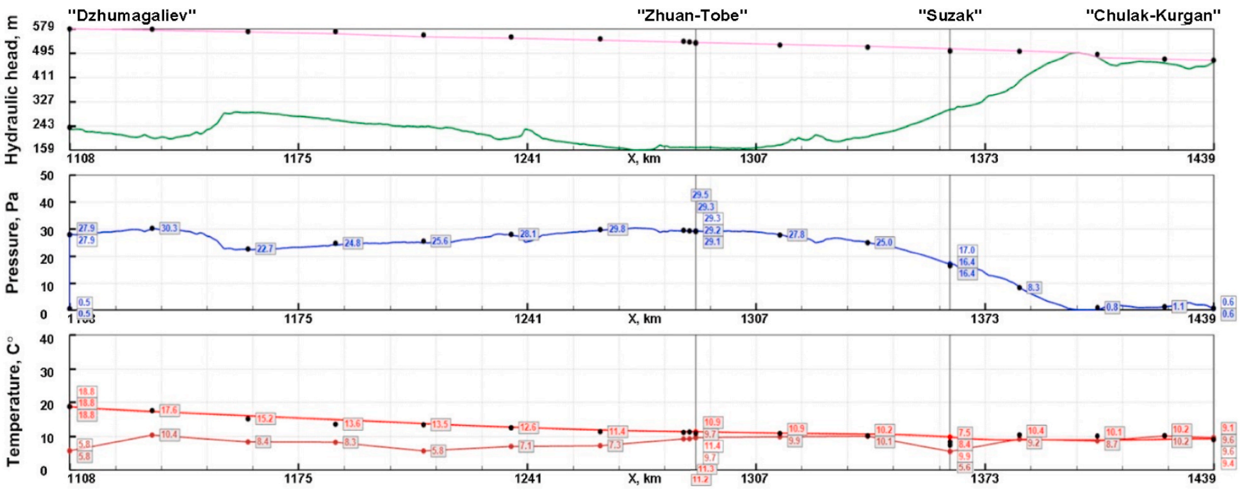

Fig. 6. Experiments (points) and calculations (lines) of hydraulic head, pressure and temperature at the "Dzhumagaliev–Chulak-Kurgan" industrial pipeline at a flow rate of 681 m^3/h and an outlet temperature of 18.8 °C.

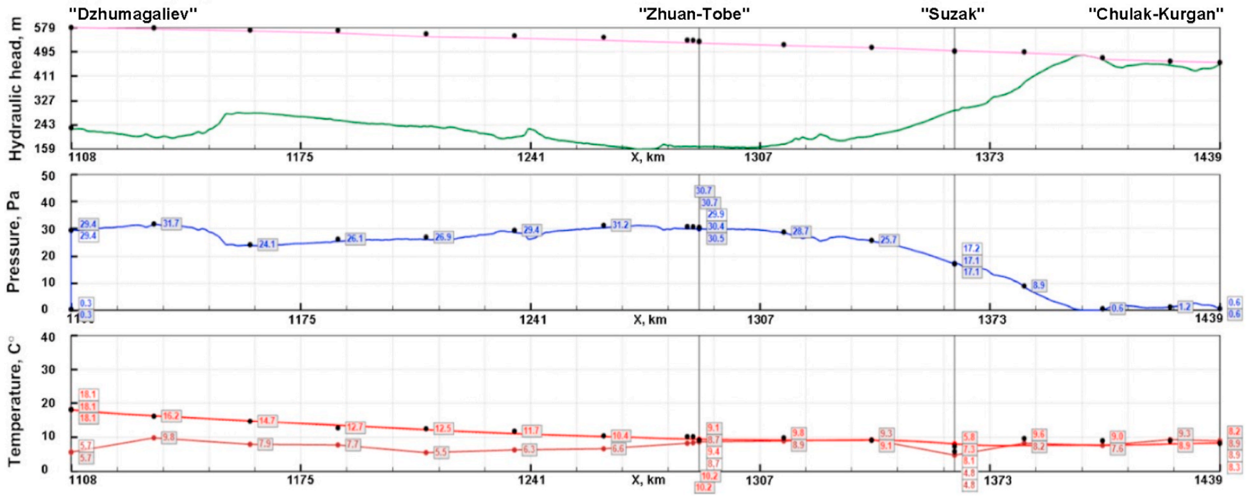

Fig. 7. Experiments (points) and calculations (lines) of hydraulic head, pressure and temperature at the "Dzhumagaliev–Chulak-Kurgan" industrial pipeline at a flow rate of 745.8 m^3/h and an outlet temperature of 18.1 °C.

7. Conclusion

1. Empirical dependences of waxy oil dynamic viscosity $\mu_p(t)$ and yield stress $\tau_0(t)$ with and without pour point depressant are obtained using the regression model. Waxy oil yield stress without pour point depressant increases sharply, starting from a temperature of 12 °C, and with pour point depressant, starting from a temperature of 0 °C. Empirical relationships $\mu_p(t)$ are used to determine the hydraulic resistance of the industrial pipeline.
2. The mathematical model of waxy oil with pour point depressant was investigated in the industrial pipeline. The system of equations of continuity, momentum and energy with closing relations was solved by the numerical method. The theoretical analysis verification was carried out with experimental data measured by the SCADA system sensors along the industrial pipeline length.
3. Thermo-hydraulic calculations of waxy oil were carried out with the SmartTran software. The calculated waxy oil data were obtained with operating parameters at the station outlet: flow rate from 681 to 745.8 m^3/h, temperature from 18.1 to 25.3 °C. It is shown that at low soil temperatures, pumping of waxy oil in the considered area occurs only when treated with pour point depressant.
4. The thermo-hydraulic calculation results of waxy oil flow hydraulic head, pressure and temperature were compared with the experimental data of the SCADA system. The agreement of calculations with the experimental data along the considered section length is shown.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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